

# **Supporting Information for Research Article**

## **Sustainable intensification of crop residue exploitation for bioenergy: opportunities and challenges**

Ioanna Mouratiadou<sup>1\*</sup>, Tommaso Stella<sup>2</sup>, Thomas Gaiser<sup>3</sup>, Birka Wicke<sup>1</sup>, Claas Nendel<sup>2</sup>, Frank Ewert<sup>2,3</sup>, Floor van der Hilst<sup>1</sup>

<sup>1</sup>Copernicus Institute of Sustainable Development, Utrecht University, Princetonlaan 8a, 3584 CB Utrecht, the Netherlands

<sup>2</sup>Leibniz Centre for Agricultural Landscape Research (ZALF), 15374 Müncheberg, Germany

<sup>3</sup>Institute of Crop Science and Resource Conservation, University of Bonn, 53115 Bonn, Germany

\*Corresponding author, e-mail: i.mouratiadou@uu.nl

### **Table of Contents**

1	Information on the case-study region .....	2
2	Data and assumptions.....	4
2.1	Residue management.....	4
2.2	Fertilisation and cover crops .....	5
2.3	Emission calculations.....	8
3	Simulated and observed SOC dynamics.....	9
4	Additional results .....	10

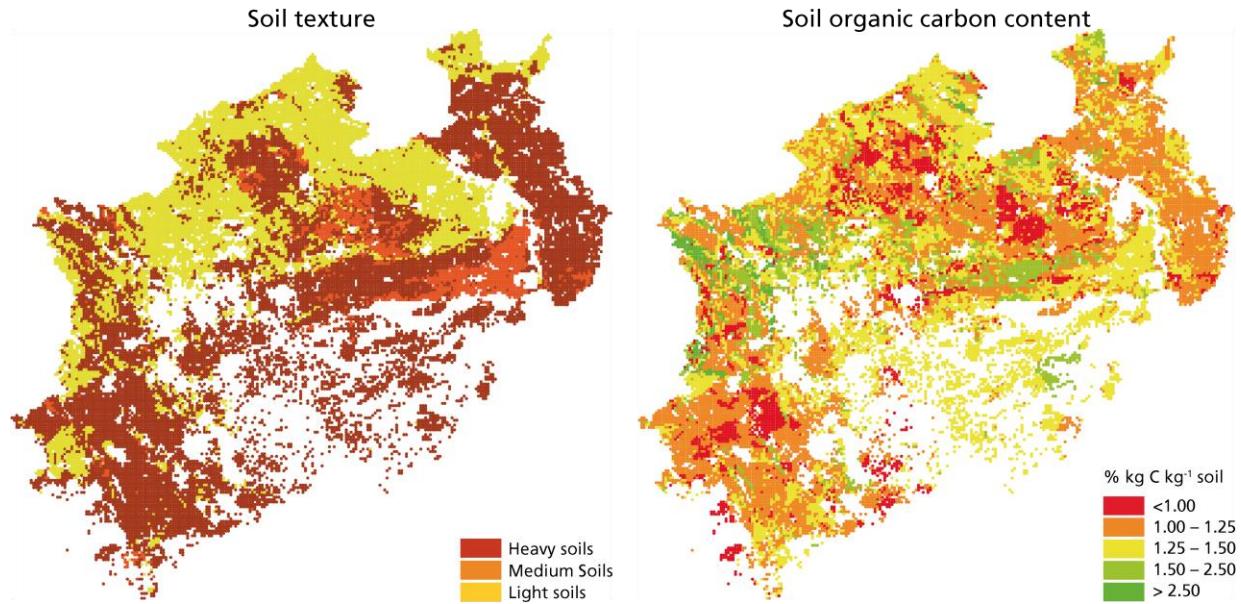
## 1 Information on the case-study region

NRW is a highly productive and intensively cultivated region located in the central western part of Germany. It is the most populous and one of the most productive German states accounting for more than 20% of Germany's Gross Domestic Product (Staatskanzlei des Landes Nordrhein-Westfalen, 2016).

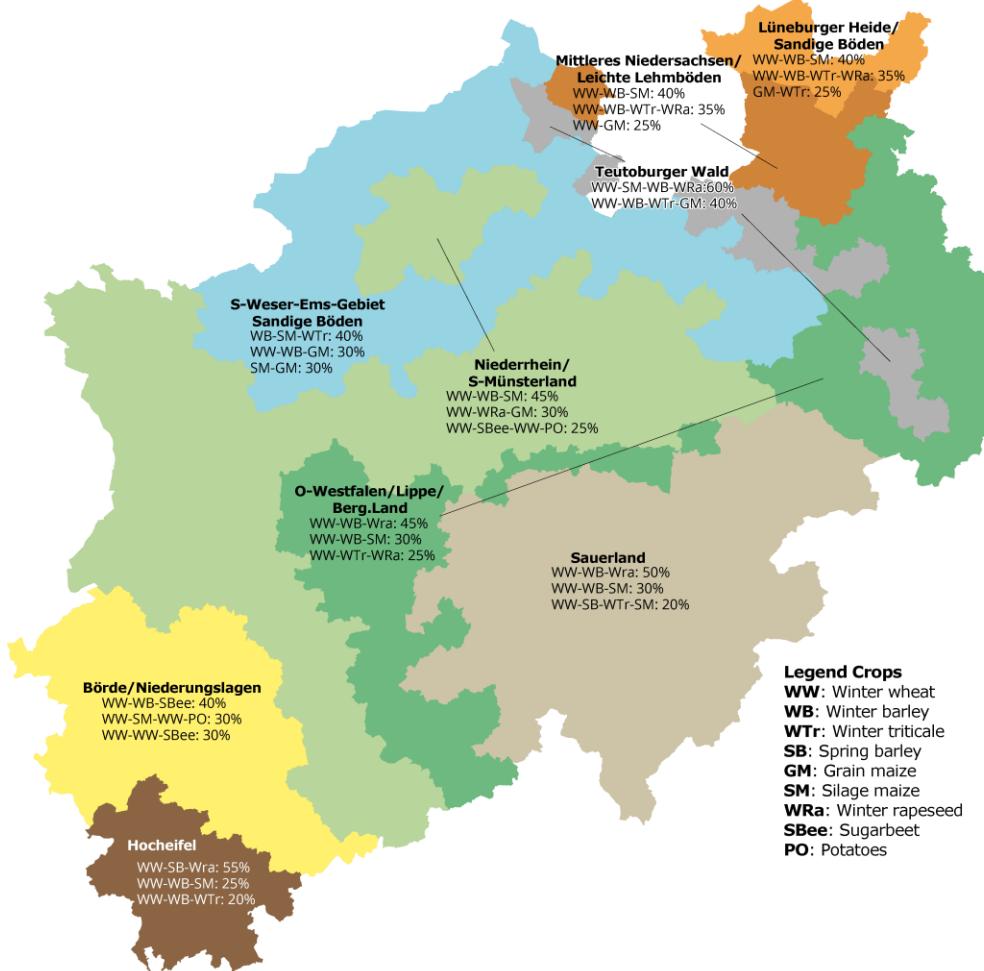


*Figure S1. Location of NRW.*

In NRW, annual rainfall varies between 600 mm in the lowland (north and west NRW) and 1,400 mm in the highlands (northeast and south NRW) and average temperature ranges between 5-10 °C (LWK NRW, 2014). The northwestern part of NRW (Munster and parts of Detmold and Dusseldorf) is mainly characterized by less fertile light soils. Soils are most fertile on the north eastern and southern plains.



*Figure S2. Texture (left) and organic carbon content (right) of soils in NRW. For the soil texture map we aggregated the 31 soil texture classes from the German soil-classification system (AG Boden, 2005) into light (sandy), medium (silty and loamy) and heavy (clayey) soils. The soil organic carbon (SOC) map shows baseyear (2000-2004) SOC levels simulated by the MONICA model after model calibration.*



*Figure S3. Combinations of pedoclimatic regions and rotations in NRW. The pedoclimatic regions are retrieved from Roßberg et al (2007) and the percentage of rotations per pedoclimatic region from Burkhardt and Gaiser (2010) based on statistical reports on cropland shares of major crops in 2007.*

## 2 Data and assumptions

### 2.1 Residue management

The equation used for the agricultural management scenarios based on the humus balance approach is shown below:

$$Bal = HumDem_c - RES_{i,c,y} \times HumRes_c - Org_i \times HumOrg - CC_i \times HumCC - HUMCO_{i,y}, \quad (1.)$$

Where, **c**: crop; **y**: year; **y'**: previous year; **Bal**: scenario-specific required humus balance level ( $H_{eq} \text{ ha}^{-1} \text{ yr}^{-1}$ ); **HumDem<sub>c</sub>**: humus demand factor per crop ( $H_{eq} \text{ ha}^{-1} \text{ yr}^{-1}$ ); **RES<sub>i,c</sub>**: residues remaining on the field (t dry matter (DM)  $\text{ha}^{-1} \text{ yr}^{-1}$ ); **HumRes<sub>c</sub>**: humus supply factor for residues ( $H_{eq} \text{ t}^{-1} \text{ DM}$ ); **Org<sub>i</sub>**: amount of applied organic fertiliser (t  $\text{ha}^{-1} \text{ yr}^{-1}$ ); **HumOrg**: humus supply factor for organic fertiliser ( $H_{eq} \text{ t}^{-1} \text{ DM}$ ); **CC<sub>i</sub>**: cover crop biomass ( $\text{t ha}^{-1} \text{ yr}^{-1}$ ); **HumCC**: humus supply factor for cover crops ( $H_{eq} \text{ t}^{-1} \text{ DM}$ ); **HUMCO<sub>i</sub>**: humus balance in previous cultivation period ( $H_{eq} \text{ ha}^{-1} \text{ yr}^{-1}$ ).

*Table S1. Humus balance data and assumptions*

Parameter or Variable	Source	Data and assumptions
<b>Bal</b>	LWK NRW (2015)	0 or 400 $H_{eq} \text{ ha}^{-1} \text{ yr}^{-1}$ depending on scenario and own assumption
<b>HumDem</b>	LWK NRW (2015)	Cereals (except maize) and winter rapeseed: 280 $H_{eq} \text{ ha}^{-1} \text{ yr}^{-1}$ Silage and grain maize: 760 $H_{eq} \text{ ha}^{-1} \text{ yr}^{-1}$ Sugar beet and potatoes: 560 $H_{eq} \text{ ha}^{-1} \text{ yr}^{-1}$ Cover crops: 140 $H_{eq} \text{ ha}^{-1} \text{ yr}^{-1}$
<b>RES</b>	MONICA	Residue yields are simulated by the model; the share of residues remaining on the field are determined at harvest by solving Eq. 1.
<b>HumRes</b>	LWK NRW (2015)	116 $H_{eq} \text{ t}^{-1} \text{ DM}$
<b>Org</b>	LWK NRW (2014)	Organic fertilization is based on organic N budget estimated at district level. See Figure S4.
<b>HumOrg</b>	LWK NRW (2015)	100 $H_{eq} \text{ t}^{-1} \text{ DM}$ ; we assume all organic fertilizers are in the form of slurry.
<b>CC</b>	MONICA	Relevant only for summer crops; yields of cover crops are simulated by the model.
<b>HumCC</b>	LWK NRW (2015)	80 $H_{eq} \text{ t}^{-1} \text{ DM}$
<b>HUMCO</b>	MONICA	Humus balance carried over from the previous cropping season. A deficit is established when the amount of residues produced by a crop plus the organic fertilization are not sufficient to meet the target balance (Bal). A surplus may exist for crops returning all the residues to the soil (e.g., winter rapeseed).

## 2.2 Fertilisation and cover crops

All fertilization strategies assume a crop-specific average N requirement to attain optimal growth and yield (target N in Table S2) derived from LWK NRW (2016). Part of this N demand is covered by the mineralization of soil organic matter and organic fertilizers. The remainder (i.e. target N – soil N supply) is applied as mineral N. The mineral N target is split into different fertilization events, with timing and relative dosage determined from recommendations (LWK NRW, 2016) (Table S2).

*Table S2. Parameters for the characterization of mineral N fertilization.*

Crop	Target N (kg ha <sup>-1</sup> )	Dosage (fraction)			Timing (fixed date or phenological stage)			Target soil depth (cm) **		
		F1	F2	F3	F1	F2	F3	F1	F2	F3
Silage maize*	190	1	-	-	31/05	-	-	60	-	-
Grain maize*	190	1	-	-	31/05	-	-	60	-	-
Spring barley	150	0.67	0.33	-	sowing	double ridge	-	60	60	
Winter-Triticale	190	0.37	0.32	0.31	15/03	double ridge	flowering	90	90	90
Winter rape	180	0.55	0.45	-	01/03	double ridge	-	90	90	-
Sugarbeet	180	0.67	0.33	-	sowing	emergence	-	90	90	-
Winter wheat	200	0.35	0.33	0.32	15/03	double ridge	flowering	90	90	90
Winter barley	180	0.39	0.31	0.3	15/03	double ridge	flowering	90	90	90
Potato	160	1	-	-	sowing	-	-	60	-	-

Source: Landwirtschaftskammer Nordrhein-Westfalen (2016) and own elaboration as described in text. Timing is either defined as a fixed date or as a phenological stage. In the latter case, fertilization is fired when the MONICA model hits a determined development stage (sowing, emergence, double ridge, or flowering).

\* Additional 20 kg N ha<sup>-1</sup> are supplied at sowing.

\*\* Used only for Fert and SI scenarios.

The way soil N supply is estimated is scenario-dependent. For the *rule-based* option, soil N supply is provided by monitoring stations covering the study area (1996-2007), which record the N availability in soil at the begin of vegetative growth for different combinations of crop sequences and soil type (Table S3) (LWK NRW, 2018). The estimated soil supply is then adjusted by the effects of cover crops and organic N management following the official recommendations (LWK NRW, 2016). In specific, the presence of a cover crop prior to the main crop increases the supply by 20 kg N ha<sup>-1</sup> and each livestock unit (corresponding to 100 kg N from organic fertilizer) increases it by 10 kg N ha<sup>-1</sup>.

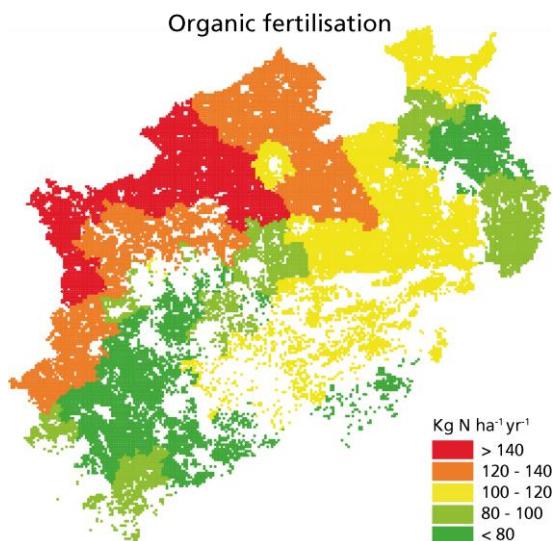
For the *optimised* option, we assume farmers are able to measure soil N supply at each fertilization event, and apply the precise amount of mineral N required to meet the target N in the rooted zone. The target N is partitioned among different events according to the same dosage rules used for the rule-based option (Table S2). Applied mineral N is adjusted to compensate for the difference between the event-specific target N (i.e. crop target N x dosage coefficient) and the mineral N content simulated in the rooted zone the day of fertilisation.

Regarding cover crop assumptions, we use mustard, as it is one of the most common ones in NRW. Sowing and harvest dates of the cover crop are set dynamically during the simulation (after the harvest of the previous main crop and no later than September 20<sup>th</sup>) in order to minimize the fallow period. Harvest of the cover crop occurs ten days before the date of sowing of the following main crop.

Table S3. Average soil N supply ( $\text{kg N ha}^{-1}$ ) for the crop sequences identified in NRW

Current crop	Soil type	Previous crop								
		Winter wheat	Winter triticale	Winter barley	Silage maize	Grain maize	Winter rape	Spring barley	Sugar-beet	Potato
Winter wheat	light	36	36	-	33	33	49	-	37	49
	med	42	42	-	46	46	49	-	43	49
	heavy	44	44	-	47	47	51	-	46	52
Winter triticale	light	30	-	30	24	29	-	30	-	-
	med	39	-	39	38	38	-	39	-	-
	heavy	42	-	42	39	39	-	42	-	-
Winter barley	light	24	24	-	24	-	-	-	-	-
	med	34	34	-	39	-	-	-	-	-
	heavy	35	35	-	42	-	-	-	-	-
Silage maize	light	22	22	22	-	27	-	-	-	-
	med	30	30	30	-	36	-	-	-	-
	heavy	32	32	32	-	30	-	-	-	-
Grain maize	light	22	28	28	27	-	26	-	-	-
	med	30	37	37	36	-	39	-	-	-
	heavy	32	31	31	30	-	34	-	-	-
Winter rape	light	23	23	23	-	-	-	23	-	-
	med	28	28	28	-	-	-	28	-	-
	heavy	28	28	28	-	-	-	28	-	-
Spring barley	light	25	-	-	-	-	-	-	-	-
	med	35	-	-	-	-	-	-	-	-
	heavy	35	-	-	-	-	-	-	-	-
Sugar-beet	light	31	-	31	-	-	-	-	-	-
	med	40	-	40	-	-	-	-	-	-
	heavy	40	-	40	-	-	-	-	-	-
Potato	light	22	-	-	-	-	-	-	-	-
	med	30	-	-	-	-	-	-	-	-
	heavy	32	-	-	-	-	-	-	-	-

For the main crops, typical sowing and harvest dates were identified for each pedoclimatic region (Table S4). The former were used to set the fixed sowing date of each crop, whereas the latter allowed defining a latest date of harvest (i.e. 15 days after typical harvest date). Harvest is triggered either at maturity, if this is reached before the latest date, or at the latest date defined.



*Figure S4. Organic fertilisation levels in NRW. The map is based on the organic N balance of farms estimated at district level (LWK NRW, 2014, Table 27, p. 52).*

*Table S4. Typical sowing and harvest dates per crop.*

Redo-climatic zone	Dates	Winter wheat	Winter barley	Grain maize	Silage maize	Winter rapeseed	Sugar-beet	Spring barley	Potato
129	Sowing	04/10	17/09	NA	25/04	11/09	NA	31/03	NA
	Harvest	15/08	17/07	NA	26/09	15/07	NA	15/07	NA
134	Sowing	04/10	17/09	NA	25/04	01/09	NA	31/03	NA
	Harvest	10/08	17/07	NA	26/09	15/07	NA	15/07	NA
141	Sowing	31/10	27/09	28/04	25/04	15/09	01/04	NA	NA
	Harvest	20/07	04/07	20/10	15/09	01/07	05/11	NA	NA
142	Sowing	16/10	27/09	28/04	25/04	15/09	01/04	NA	NA
	Harvest	20/07	04/07	20/10	15/09	01/07	05/11	NA	NA
143	Sowing	04/10	17/09	NA	25/04	15/09	NA	NA	NA
	Harvest	10/08	10/07	NA	15/09	15/07	NA	NA	NA
146	Sowing	NA	NA	NA	NA	NA	NA	NA	NA
	Harvest	NA	NA	NA	NA	NA	NA	NA	NA
147	Sowing	NA	NA	NA	NA	NA	NA	NA	NA
	Harvest	NA	NA	NA	NA	NA	NA	NA	NA
148	Sowing	16/10	27/09	28/04	25/04	15/09	01/04	NA	NA
	Harvest	20/07	04/07	01/10	15/09	01/07	05/11	NA	NA
191	Sowing	04/10	17/09	NA	25/04	01/09	NA	NA	NA
	Harvest	10/08	17/07	15/10	20/09	22/07	NA	NA	NA
German average (1980-2010)	Sowing	09/10	20/09	29/04	29/04	26/08	10/04	31/03	24/04
	Harvest	10/08	18/07	28/09	28/09	26/07	07/10	09/08	16/09

Source: Bundessortenamt (2000). For each crop, missing dates (NA) were replaced by the average of crop operations in NRW pedoclimatic regions for which the data is available. For potato, we used the German average as retrieved from the German weather service (DWD) phenological database (DWD Climate Data Center, 2018). Winter triticale dates are assumed as the average of winter wheat and winter rye. For the codes of the pedoclimatic regions see Figure S2.

## 2.3 Emission calculations

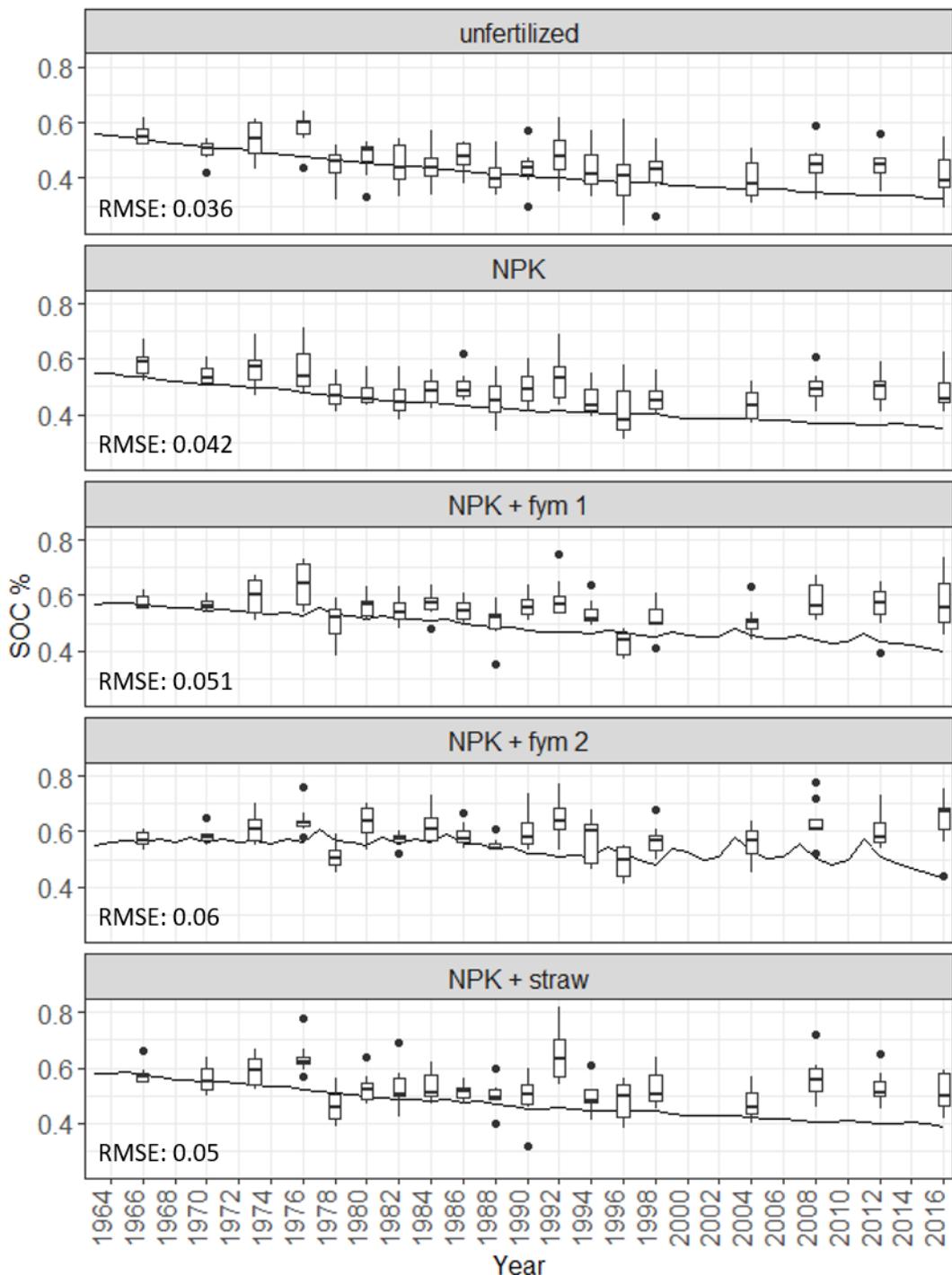
*Table S5. N concentration of above-ground residues.*

Crop	N concentration (kg N kg <sup>-1</sup> DM)
Winter wheat	0.006
Winter triticale	0.006
Winter barley	0.007
Spring barley	0.007
Silage maize	0.006
Grain maize	0.006
Winter rape	0.015
Sugarbeet	0.016
Potato	0.019
Cover crop	0.015

Source: IPCC (2006)

Note: for winter rape and the cover crop (mustard) we assumed the value for non-N fixing forages.

### 3 Simulated and observed SOC dynamics



*Figure S5.* Simulated (continuous lines) and observed (boxplots) SOC dynamics from long-term field experiments carried out in Müncheberg, Germany. Details about the treatments are reported by Rogasik et al. (2004); NPK = mineral fertilization, fym = farmyard manure. For Fym 1, fym 2 and straw treatments respectively 1.2, 3.2 and 2.0 t DM ha<sup>-1</sup> of organic manure were applied to root crops (Stella et al., 2019).

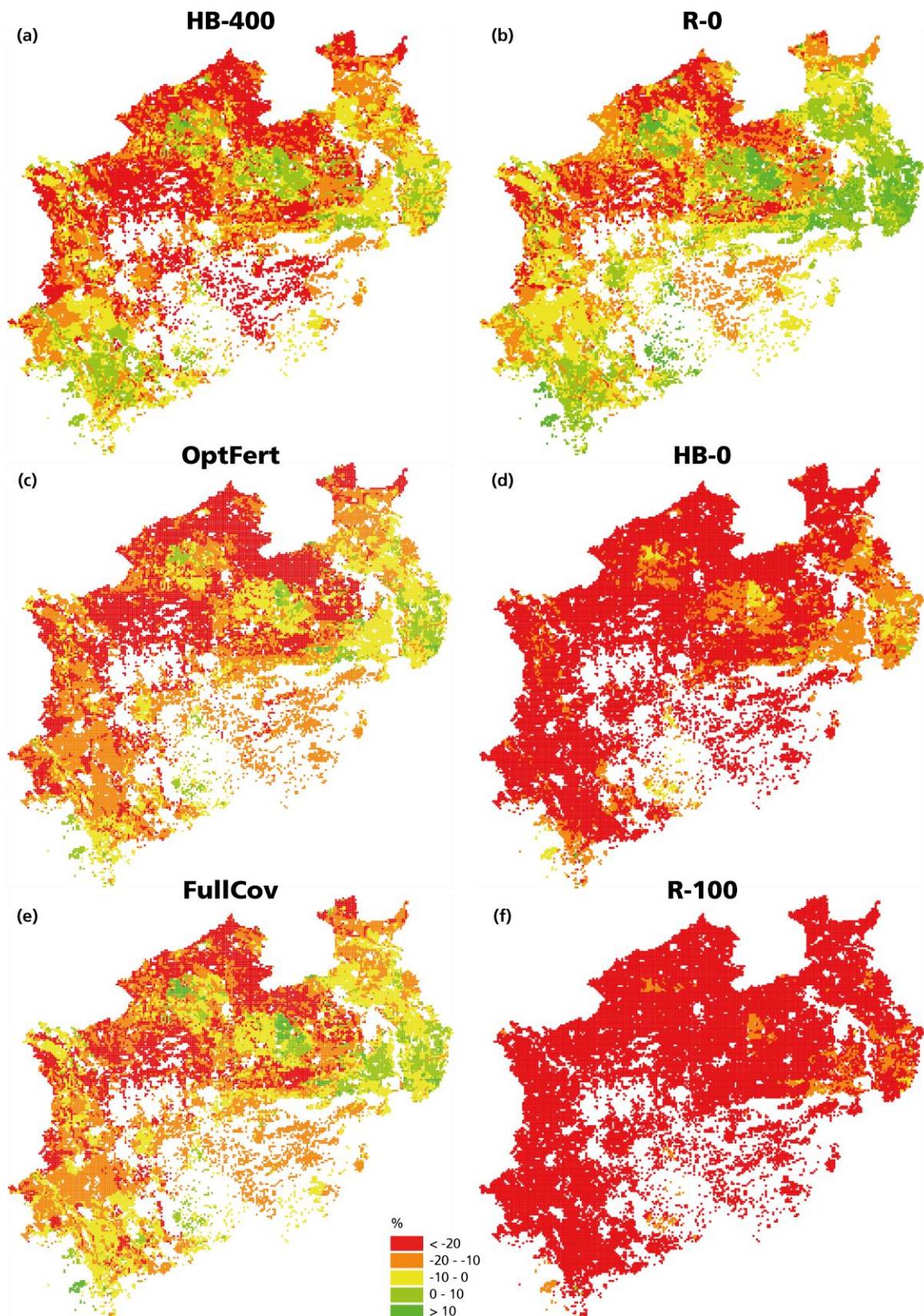
## 4 Additional results

*Table S6. Level of technical potential and environmental impacts at the level of NRW per agricultural management scenario in 2050. For each variable, we present absolute values and per cent change to the Ref scenario. The estimation of the variables is based on the equations shown in Section ‘Estimation of technical residue potentials and GHG emissions’.*

	Technical potential		$\Delta\text{SOC}$		Nitrate leaching		GHG emissions	
	PJ yr <sup>-1</sup>	%	kt C yr <sup>-1</sup>	%	kt N yr <sup>-1</sup>	%	kt CO <sub>2-eq</sub> yr <sup>-1</sup>	%
Ref	48	-	-281	-	108	-	2623	-
SI	50	5	-257	-8	91	-16	1752	-33
HB-400	52	9	-283	1	109	1	2518	-4
OptFert	47	-2	-290	3	91	-16	1865	-29
FullCov	48	0	-242	-14	102	-5	2491	-5
R-0	0	-100	-156	-44	121	12	3465	32
HB-0	105	118	-425	52	97	-10	1644	-37
R-100	145	201	-527	88	90	-16	958	-63

*Table S7. GHG emissions from the displacement of fossil fuels by bioethanol, changes in SOC, N<sub>2</sub>O emissions, and emissions for the production of fertilisers in 2050 (10<sup>3</sup> tonnes CO<sub>2-eq</sub> yr<sup>-1</sup>). For each variable, we present absolute values and per cent change to the Ref scenario.*

	Displaced fossil fuel emissions		Emissions equivalents of SOC changes		N <sub>2</sub> O emissions		Fertiliser production emissions	
	Absol.	%	Absol.	%	Abs.	%	Abs.	%
Ref	-1225	0	1029	0	1681	0	1139	0
SI	-1284	5	942	-8	1379	-18	715	-37
HB-400	-1338	9	1038	1	1679	0	1139	0
OptFert	-1195	-2	1062	3	1288	-23	710	-38
FullCov	-1224	0	888	-14	1729	3	1098	-4
R-0	0	-100	572	-44	1754	4	1139	0
HB-0	-2672	118	1558	52	1619	-4	1139	0
R-100	-3691	201	1931	88	1578	-6	1139	0



*Figure S6. Spatially explicit ΔSOC in topsoil between baseyear and 2050 for different agricultural management scenarios.*

## References

- AG Boden. (2005). *Bodenkundliche Kartieranleitung (KA5). 5th revised edition.* Stuttgart: Bundesanstalt für Geowissenschaften und Rohstoffe, E. Schweizerbart'sche Verlagsbuchhandlung.
- Bundessortenamt. (2000). *Planungs-, Informations- und Auswertungssystem für Feldversuche (PIAF).* Retrieved from <https://www.bundessortenamt.de/internet30/index.php?id=155>
- Burkhardt, J., & Gaiser, T. (2010). *Modellierung der Folgen des Klimawandels auf die Pflanzenproduktion in Nordrhein-Westfalen.* Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen.
- DWD Climate Data Center. (2018). *Phenological observations of crops from sowing to harvest (annual reporters, historical), Version v005.*
- IPCC. (2006). Chapter 11. N2O emissions from managed soils, and CO2 emissions from lime and urea application. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (pp. 11.1-11.54). Retrieved from [https://www.ipcc-nccc.iges.or.jp/public/2006gl/pdf/4\\_Volume4/V4\\_11\\_Ch11\\_N2O&CO2.pdf](https://www.ipcc-nccc.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf)
- LWK NRW. (2014). *Nährstoffbericht NRW 2014.* Landwirtschaftskammer Nordrhein-Westfalen.
- LWK NRW. (2015). *Humus und Bodenfruchtbarkeit.* Landwirtschaftskammer Nordrhein-Westfalen.
- LWK NRW. (2016). *Ratgeber Pflanzenbau und Pflanzenschutz.* Münster, Germany: Landwirtschaftskammer Nordrhein-Westfalen.
- LWK NRW. (2018). *Durchschnittliche Nmin-Richtwerte—5jähriges Mittel.* Retrieved from Chamber of Agriculture North Rhine-Westphalia (LWK NRW) website: <https://www.landwirtschaftskammer.de/landwirtschaft/ackerbau/pdf/nmin-richtwerte-5-j-mittel.pdf>
- Roßberg, D., Michel, V., Graf, R., & Neukampf, R. (2007). Definition von Boden-Klima-Räumen für die Bundesrepublik Deutschland. *Nachrichtenblatt Deutscher Pflanzenschutzdienst*, 59(7), 155–161.
- Staatskanzlei des Landes Nordrhein-Westfalen. (2016). NRW entdecken. Retrieved 9 September 2016, from WIR IN NRW DAS LANDESPORTAL website: <https://www.land.nrw/de/land-und-leute/nrw-entdecken>
- Stella, T., Mouratiadou, I., Gaiser, T., Berg-Mohnicke, M., Wallor, E., Ewert, F., & Nendel, C. (2019). Estimating the contribution of crop residues to soil organic carbon conservation. *Environmental Research Letters.* Retrieved from <http://iopscience.iop.org/10.1088/1748-9326/ab395c>